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**HIGH ALPHA FEEDBACK CONTROL FOR AGILE HALF-LOOP
MANEUVERS OF THE F-18 AIRPLANE**

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ABSTRACT

We developed a nonlinear feedback control law for the F/A-18 airplane that provide time-optimal or agile maneuvering of the half-loop maneuver at high angles of attack. Our feedback control law was developed using the mathematical approach of singular perturbations, in which the control devices considered were conventional aerodynamic control surfaces and thrusting. The derived nonlinear control law was used to simulate F/A-18 half-loop maneuvers. The simulated results at Mach 0.6 and 0.9 compared well with pilot simulations conducted at NASA.

I. INTRODUCTION

Modern high performance combat aircraft are being designed to provide an increased level of dynamic maneuverability-supermaneuverability. The performance requirements for such aircraft call for capabilities to:

- (1) rapidly accelerate or decelerate
- (2) turn tightly and quickly
- (3) change maneuver conditions rapidly

These require high levels of agility and maneuverability at high angles of attack (α). High performance aircraft in high α maneuvers experience significant nonlinearities and undergo large roll, pitch and yaw rates in performing combat maneuvers in least time. Aircraft and pilot limits are easily exceeded. The resulting impact is the need for automated nonlinear feedback control to provide combat maneuvers with optimal performance within the limitations of aircraft and pilot. We seek the development of such control laws for the F/A-18 airplane in its performance of some basic maneuvers at high α : half-loop, split-S, Herbst's, level turn, 360° roll, unloading g 's, etc. Our approach is a four-step procedure in the development of a nonlinear feedback control law for a combat maneuver. It consists of (1) singular perturbation analysis, (2) Pontryagin's maximum principle analysis, (3) closed-loop synthesis of optimal open-loop control and Fliess' nonlinear feedback regulation concepts and (4) simulation analysis.

Our research procedure, therefore, consists of the following goals and approaches.

A. Singular Perturbation Analysis

Goal: To construct automatic nonlinear feedback control laws for agile maneuvering of the F/A-18 airplane at high α .

Approach: Apply singular perturbation techniques to derive outer and transition layers of nonlinear feedback control laws.

B. Pontryagin's Maximum Principle Analysis

Goal: To generate a family of open-loop controls for optimal agile (i.e., minimum time) maneuvering of the F/A-18 airplane at high alpha.

Approach: Apply Pontryagin's maximum principle and singular arc conditions of optimal control theory to obtain candidates for optimal open-loop controls.

C. Closed-Loop Synthesis

Goal: To construct nonlinear feedback laws for optimal agile maneuvering of the F/A-18 airplane at high alpha.

Approach: Synthesize the family of open-loop controls obtained using Pontryagin's maximum principle into a nonlinear feedback control law and employ Fliess' nonlinear feedback regulation concepts to construct nonlinear feedback control.

D. Simulation and Comparison Analysis

Goal: To establish relative merits of feedback control laws

Approach: Simulate combat maneuvers using feedback control laws and compare the performance of the optimal feedback control law against that of the "bench mark" singular perturbation technique.

Singular perturbation analysis provides a direct method for constructing a nonlinear feedback control law. Fast and slow variables together with equilibrium equations for the fast variables permit construction of an "outer layer" feedback control law in terms of the slow variables. Transition feedback control is derived to transfer the state to and from the outer layer. This approach while not always providing a feedback control that is globally optimal it does give relative simple nonlinear expressions that yield insight into optimal maneuvering and that serve as a bench mark in the evaluation of optimal open-loop controls.

Pontryagin's maximum principle provides an indirect method for constructing a nonlinear feedback control law. Since this principle is a necessary condition to be met by an optimal open-loop control

additional conditions are required to establish optimality. The maximum principle together with transversality conditions yield a two-point boundary valued problem for generating candidate optimal open-loop controls. By varying the initial and final states (e.g., Mach number, altitude) this technique provides a family of open-loop controls that span a region of the state space.

The parametrized family of open-loop controls obtained by the maximum principle analysis is to be synthesized into a closed-loop control law. The adjoint state variables and the switching function of the parametrized family are utilized to construct a closed-loop control. The final step is to implement the nonlinear feedback control laws into computer code, to simulate state time histories and to compare the responses.

We have carried out parts of the above four-step procedure in the development of nonlinear feedback control laws for the half-loop maneuver of the F/A-18. Our present research work to derive nonlinear feedback control for high angle of attack maneuvers started with an application to the T-2C aircraft, Refs. 1 and 2. Therein, using the singular perturbation technique, Refs. 7-14, and the maximum principle, Ref.15, together with numerical optimization software, Refs. 16 and 17, we derived nonlinear control laws for a constant speed model of the T-2C aircraft to perform a pitch-up maneuver. Since then our research work has focused on applying the above four-step procedure to the F/A-18 airplane.

II. RECENT F-18 RESEARCH RESULTS

The application proposed in Ref. 3 of the above described four-step procedure to the F/A-18 fighter airplane for the half-loop maneuver is given partially in Refs. 4,5 and 18. A nonlinear feedback control law for agile half-loop maneuvers of the F-18 is derived in Ref. 4 using the singular perturbation technique. The derived control rotates the velocity vector (i.e., the flight path angle) through 180° at a maximum equilibrium pitch rate with a nearly constant 38° angle of attack (i.e., near maximum lift conditions). The half-loop simulations for entry Mach numbers 0.6 and 0.9 at 15,000 feet altitude, Refs. 4 and 5, yield 9 seconds and 13 seconds, respectively, for the longitudinal

portion of the half-loop maneuver. Those results compare well with NASA's pilot simulated half-loop maneuvers which gave 15 seconds and 22 seconds, respectively, for the same entry conditions.

The nonlinear control law derived in Ref. 4 is unconstrained with respect to pilot load factors. That is, such load factors were not enforced in its development. But pilot load factors were computed in the executions of the derived nonlinear control law to determine the regions in which such pilot limitations may be violated. The normal load factor exceeded 7.5 g's only in the first second of the 0.9 Mach entry case. At such Mach numbers the control could be limited to prevent violations of a prescribed maximum load factor. The modified control would add at most another second onto the execution time of the half-loop maneuver.

The derived nonlinear control law does produce a relatively fast half-loop maneuver that may be useful in practice. Also, it provides a good baseline for half-loop maneuver studies of the F/A-18 airplane. It is particularly useful as a bench mark for time optimal studies. The derived law is feedback control and is nonlinear. It has been coded into a subroutine module of table look-up values, Ref. 4. We have just recently reduced the table of look-up values to three simple polynomial equations. The derived control law consists of three parts. The first and third portions of the nonlinear feedback control law are transitions solutions which minimize the time to bring the aircraft from the initial trim values to the outer layer (i.e., second portion) and from the outer layer to the final values of the half-loop maneuver. The stabilator angle feedback control is bang-bang in these first and third portions.

The second portion is an outer layer solution of singular perturbation theory in which the stabilator angle is a nonlinear function of Mach number, flight path angle and altitude. The angle of attack is nearly constant at the stall maximum lift value (i.e., 36° to 38°). The pitch rate, which is a function of Mach number, flight path angle and altitude, is the value that maximizes the rate of change of the flight path angle while providing equilibrium to the angle of attack and the pitch rate differential equations of motion. This second portion of the control law is defined by surfaces (i.e.,

table look-up values) for the outer layer values of angle of attack, pitch rate and stabilator angle. Three polynomial equations are used by the feedback subroutine to determine the outer layer values for Mach number, flight path angle and altitude states. The data covers angle of attack from 0° to 90° , Mach numbers from 0.05 to 0.9, flight path angles from 0° to 180° and altitudes from sea level to 60,000 feet. The feedback subroutine uses the three polynomial equations to compute the outer layer values of the feedback control law value of the stabilator angle for the outer layer.

III. F-18 RESEARCH WORK IN PROGRESS

The nonlinear feedback control law derived using singular perturbation analysis, while not being necessarily optimal, provides a baseline for time optimal half-loop maneuver studies. We are currently using the maximum principle approach to generate candidate solutions for time optimal half-loop maneuvers of the F-18 airplane, Ref. 18. We are also using the maximum principle to pitch-up the F-18 airplane to 90° angle of attack in minimum time for the Herbst's maneuver. Furthermore, we are using the singular perturbation technique to develop a nonlinear feedback control law for the split-S maneuver of the F-18 airplane. This work will be completed and documented over the next six months. Specifically, we are addressing the following problems:

PROB 1. Use the maximum principle to derive time optimal half-loop maneuvers and compare with singular perturbation control law time responses.

PROB 2. Use singular perturbation analysis to develop a nonlinear feedback control law for the split-S maneuver.

PROB 3. Use the maximum principle to optimize the pitch-up to 90° angle of attack for the Herbst's maneuver.

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